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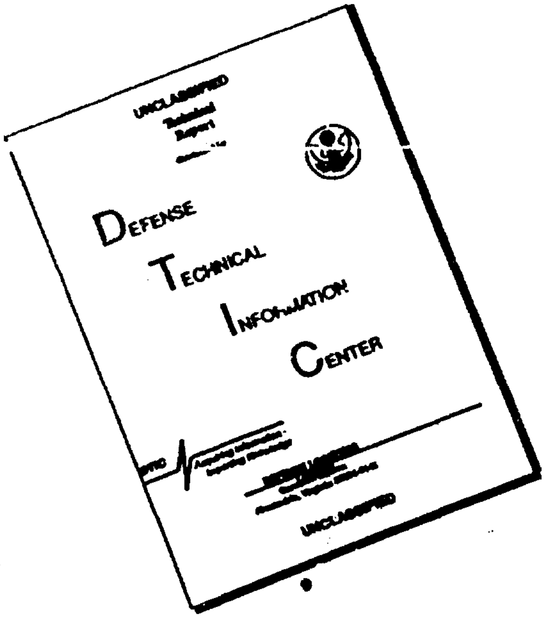


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| 13 ABSTRACT(MAX 200 WORDS) THIS PAPER COMPARES THE EXPERIMENTAL RESULTS OF HIGH STRAIN RATE DEFORMATION AND TARGET PENETRATION STUDIES OF AN EXPLOSIVELY FORMED PROJECTILE (EFP) WARHEAD DESIGN WITH THE VALUES PREDICTED USING A FINITE ELEMENT ANALYSIS (FEA) MODELLING TECHNIQUE. UTILISATION OF EXPERIMENTALLY DETERMINED HIGH STRAIN RATE (UP TO 9000s -1) MATERIALS PROPERTIES IN THE FEA PREDICTION OF EFP LINER FORMATION AND TARGET PENETRATION SIMULATION SHOWED GOOD AGREEMENT WITH THE EXPERIMENTALLY DETERMINED RESULTS. | | |
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# The Modelling of High Strain Rate Deformation and Penetration Problems Using Finite Element Analysis.

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SUMMARY This paper compares the experimental results of high strain rate deformation and target penetration studies of an explosively formed projectile (EFP) warhead design with the values predicted using a finite element analysis (FEA) modelling technique. Utilisation of experimentally determined high strain rate ( up to $9000s^{-1}$ ) materials properties in the FEA prediction of EFP liner formation and target penetration simulation showed good agreement with the experimentally determined results.

## 1. INTRODUCTION

Dynamic materials modelling codes including FEA techniques are extensively used in both the design and performance enhancement of modern warheads such as th EFPs. FEA modelling codes are also utilised extensively to describe the level of target damage associated with an impacting EFP penetration warhead. Independent of the modelling code used, accurate, high strain rate mechanical properties and/or constitutive models for specific warhead and target component materials are required to closely model EFP formation or EFP target interaction. To provide this data a wide range of high strain rate test techniques have been developed. To date, however, these material's properties have almost exclusively been determined by testing as-received materials.

Previous work proposed that materials used in explosive filled devices, and in particular warheads with EFP liners, are subjected to a severe shock loading pulse, during explosive loading and prior to the commencement of plastic flow [1]. This shock loading was shown to influence subsequent material flow behaviour. A shock pulse of the magnitude associated with the explosive loading and formation of a conventional EFP, dramdatically changes both the microstructure and hardness of liner materials[1-3]. Recent, high strain rate testing of similarly shock-hardened iron and copper samples, suggests that a minimum two fold increase in yield stress could be expected for both these materials after shock hardening [1,4,5]. More particularly, the magnitude of this shock hardening effect on the subsequent materials properties will influence the ability of FEA modelling codes to accurately predict metal flow.

In recent work, materials models based on the high strain test data measured in compression at strain rates from $10^{-1}$ to $9000^{-1}$ for both iron and copper in the as-received and shock-hardened condition have been used to predict material flow during the formation of an EFP [1,6]. The results of this work indicated that using the ZeuS PC FEA modelling code and materials' flow stress models, based on shock-hardened properties, provided good agreement with experimental results [6].

The present program sought to utilise these newly developed materials models, based on shock-hardened materials properties, to predict both the formation and geometric configuration of an EFP as well as EFP target impact penetration damage.

## 2. EXPERIMENTAL

### 2.1 EFP liner design and testing

Materials used for EFP liner manufacture were rolled and heat-treated, high purity, 0.015% C, Remco iron plate and rolled OFHC copper plate conforming to Australian Standard AS.2738.2, Alloy 101. In quasi-static testing the as-received Remco iron had an ultimate tensile strength of 290 MPa, hardness of 62 HV(100g) and an elongation of 52%. The respective property values for copper were 180 MPa, 126 HV(100g) and 40%.

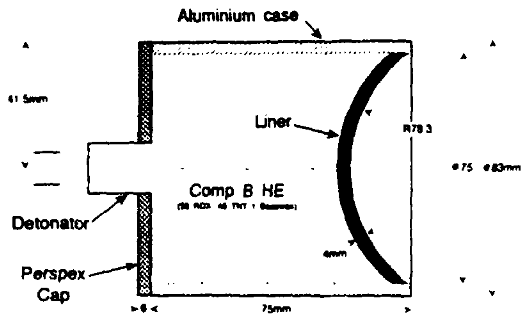


Figure 1. Details of EFP warhead design.

Details of the EFP warhead design are provided in Figure 1. Copper liners were press-formed from rolled sheet, while Remco iron liners were machined from as-received plate. The measured grain size of the as-formed liners was 0.02 mm and 0.03 mm for the iron and copper respectively. Liner surfaces were fine polished to remove surface defects before assembly into the casing, and filled with open-cast Composition B (55:45 RDX: TNT) high explosive.

Two of each warhead type were initiated with electronic bridge wire detonators and fired at 65 mm thick, mild steel target plates positioned at 1.5 m from the warhead. High speed x-ray photographs of EFP liner formation were taken at several positions along the EFP flight path. After testing the target panel was sectioned in the through-thickness direction and the penetration profile recorded.

2.2 Finite Element Analysis

All EFP and EFP/target interaction modelling was performed with the ZeuS [7] computer code. ZeuS is a IBM-PC computer based, two-dimensional explicit Lagrangian finite element analysis code. The ZeuS code utilises constant strain, triangular elements, generally in a quad arrangement, to model deformation problems in axisymmetric or plain strain mode. For inert solid materials ZeuS employs the Mie-Gruneisen equation of state for hydrostatic behaviour, while explosive materials detonation products are modelled using the Gamma Law, ideal gas equation of state. After yield, material flow is modelled using the von Mises criterion with provision for strain and strain-rate hardening, effects.

The materials model for both the Remco Fe and OFHC Cu liners utilised the shock-hardened dynamic materials properties, while the mild steel target materials model reflected the properties of the as-received Fe. Identical EFP warhead simulation mesh models were used for all modelling runs, and simulation parameters for each material were kept constant, except for the requisite changes in stress/strain behaviour. The simulation was separated into EFP formation and EFP/target interaction.

For EFP formation, initial runs indicated that there was no significant improvement in the simulation quality, and obvious penalties in CPU time, for an EFP liner with mesh finer than 30 by 3 elements and explosive 30 by 20 elements. The warhead casing, cap and explosive were dropped from the simulations at 35 ms, after which time monitoring of EFP tip velocity, showed that they had negligible influence on either further formation or the final velocity of the modelled EFP. For the EFP/target interaction simulation the EFP liner mesh was as previously defined, while the steel target was modelled using a variable size mesh of 30 by 20 elements with an expansion factor from the centre top of the target of 3% in the transverse direction and 2% in the longitudinal direction. Once generated the physical model was run in ZeuS. Output data manipulation was accomplished in the ZeuS graphical post-processor to generate object mesh deformation as a function of time.

3. RESULTS

3.1 EFP formation

For each liner material two warheads were detonated and sequential x-ray shadow-graphs of the forming projectile were recorded at time intivals up to 861 μs following detonation. Early flash x-rays showed a small amount of spalling from the trailing rim of both types of EFP liners during the initial stages of warhead formation. The weight of recovered warheads suggests that the amount of material lost from the liner was generally less than 10 g, even when a small fragment of the warhead detached during flight. For each liner type there was some shot to shot variation both in final EFP shape and the quantity of material lost from the trailing edge. A typical, soft - recovered Remco iron warhead with a small fragment missing towards the trailing edge (arrow)is shown in Figure 2.

Figure. 2. Recovered Remco iron warhead.

Typical x-ray cross-section of the fully formed iron and copper EFP is shown in Figures 3a and 3b respectively. The external and internal profile of the formed projectile taken from the x-ray negative is shown as a dotted outline. acquired from shocked material are shown in Figures 3a and 3b (solid outlines). These images show that the higher flow stress iron liner has resulted in a projectile having an L/D ratio of approximately 1 compared with the more highly worked copper projectile having a L/D ratio of approximately 2.

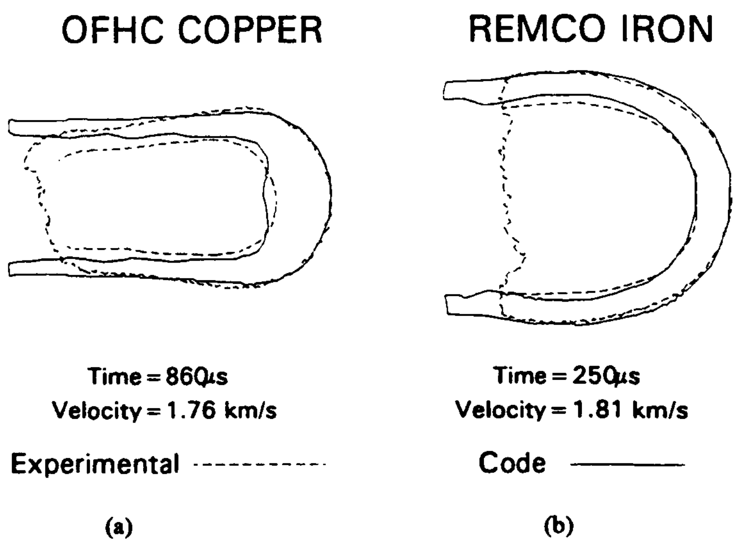


Figure 3. Experimental and FEA predicted Cu and Fe EFP liner cross-sections at specified times.

### 3.2 EFP Modelling

Some difficulty was experienced in modelling the gas leakage at both the liner/charge casing interface as well as that of the casing and perspex top. Although several schemes were tested to mitigate this effect the simplest and most effective modelling technique was found to be the removal of the charge casing where it overlapped the liner and perspex top in the simulation.

The EFP formation predictions produced by the ZeuS modelling code using compression flow stress/strain data

### 3.3 EFP Target Penetration

Cross-sections of the experimental and modelled target penetration profiles for the Remco iron and OFHC Cu EFPs are shown in Figures 4 and 5. As with EFP formation there was some variation in the experimental target hole profiles. Close examination of the EFP x-ray photographs indicated that this variation was attributable to slight EFP yaw with the resulting variation in EFP attitude relative to the target.

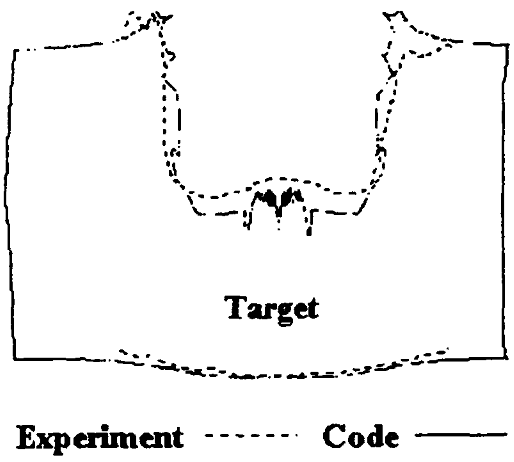


Figure 4. Comparison of target penetration cross-section produced by Cu EFP.

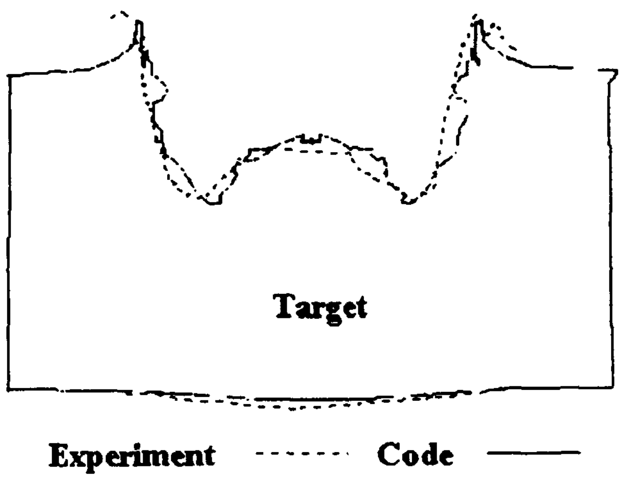


Figure 5. Comparison of target penetration cross-section produced by Fe EFP.

## 4. DISCUSSION

It was generally observed that the defined problem was not a simple one to model, especially due to the requirements of optimising both initial EFP shape as well as subsequent target penetration. It was found that by using a range of simulation properties and parameters it was possible to more closely approximate the EFP experimental results, although, the resulting improvements in EFP shape were accompanied by a subsequent reduction in consistancy of the predicted hole profile. The predicted EFP cross-sections and penetration profiles are accordingly a compromise between shape accuracy and subsequent penetration quality.

### 4.1 EFP Formation

Both of the predicted EFP velocities were within 10% of the experimentally measured values. Comparisons of experimental and FEA predicted EFP dimensions generally showed good agreement, although the FEA program did demonstrate some difficulties with the accurate simulation of the EFP tail and head shape.

Additionally, the FEA simulations were unable to accurately model the liner material failure and loss which occurred at the rear edge of both of the experimental Cu and Fe EFPs. Attempts to model this failure, using a simple model based on a failure strain criterion, were quantitatively unsuccessful and highlighted the total lack of an accurate, comprehensive technique for modelling materials failure in this type of simulation.

### 4.2 EFP-Target Penetration

As illustrated in Figures 4 and 5 experimental and predicted EFP-target penetration again showed good agreement and the overall modelled penetration hole depth, diameter and crater shape were generally within 10% of the experimental profile. As with EFP formation, there was some shot to shot variation in target penetration characteristics which could be directly attributed to EFP yaw. The observed differences between prediction and experiment were of the same order as the experimental shot to shot variation.

## 5. CONCLUSIONS

This paper has illustrated the capabilities of the current generation of FEA programs to confidently simulate complex, high strain rate materials deformation and interaction processes. Comparisons of experimental and FEA simulated EFP formation including velocity as well as shape and target penetration dimensions were generally within 10%.

FEA programs are a powerful tool which with operator experience and the availability of accurate materials property data can provide both the researcher and design engineer with an unparalleled predictive/analytical capability. Accurate solutions are, however, only possible where materials constitutive models are available for similar conditions to those experienced during the dynamic deformation processes.

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